CRREL REPORT 92-16

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Laboratory Investigation of Trash Rack Freezeup by Frazil Ice

Annika Andersson and Steven F. Daly

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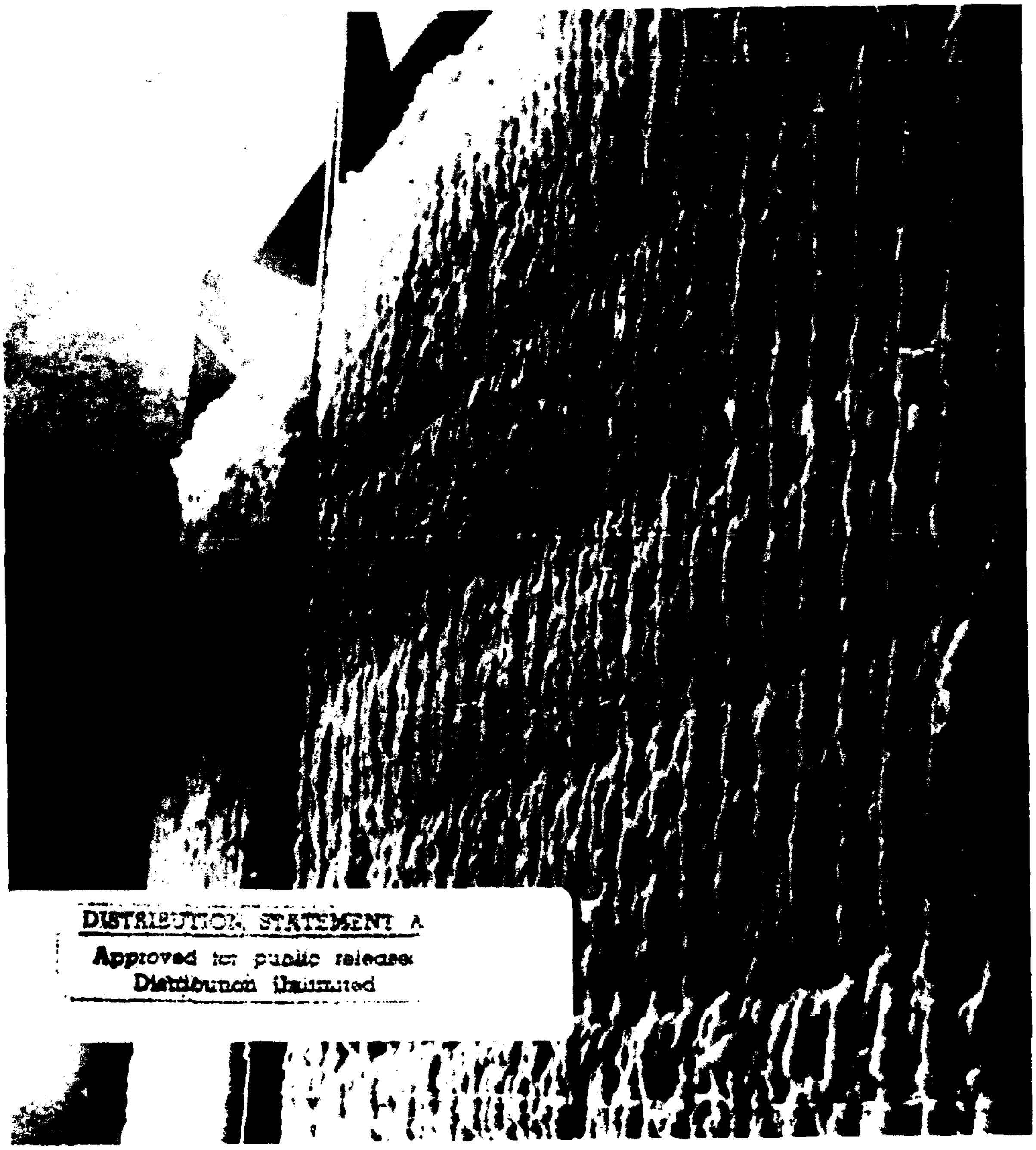

Abstract

A series of tests was conducted in a refrigerated flume facility to determine the ice accumulation pattern on models of water intake trash racks. Data gathered included the flow velocity, the water temperature and the porosity of the accumulated frazil ice (mean porosity is 0.67). Frazil accumulates first on the upstream face of the trash rack bars (being insensitive to bar shape), and then bridges between individual bars near the water surface, proceeding downward until the entire trash rack is blocked. Flow through the rack became highly nonuniform during the accumulation process.

Cover: Trash rack in the power plant of Lilla Edet in Sweden completely blocked by frazil ice (photo courtesy of the Swedish State Power Board).

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, *Metric Practice Guide*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Laboratory Investigation of Trash Rack Freezeup by Frazil Ice

Annika Andersson and Steven F. Daly

September 1992

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

PREFACE

This report was prepared by Annika Andersson, Research Engineer, Luleå University, Luleå, Sweden, and Steven F. Daly, Research Hydraulic Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Directorate of Civil Works, Office of the Chief of Engineers, under the *Ice Engineering Program*; Work Unit 32397, *Ice Control at Intakes*.

Technical review was provided by Dr. G. Ashton of CRREL and Dr. T. Carstens of the Norwegian Hydrotechnical Laboratory, Trondheim, Norway.

The authors acknowledge the help they received from John J. Gagnon, who operated the refrigerated flume facility and assisted in all the experiments, and Nancy Perron, who made all of the thin sections.

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Laboratory Investigation of Trash Rack Freezeup by Frazil Ice

ANNIKA ANDERSSON AND STEVEN F. DALY

INTRODUCTION

Trash racks, structures placed at the entrances of water intakes to exclude unwanted material, often become blocked by the accumulation of frazil ice. They can be blocked suddenly, with little warning, leading to the unanticipated shutdown of downstream facilities. There is little quantitative understanding of how trash racks become blocked by frazil. The difficulty in developing this quantitative understanding results directly from the conditions under which blockage occurs: sporadically, suddenly, often late at night, underwater and under severe weather conditions. Opportunities for observation and measurement are obviously limited.

In this report, a series of laboratory experiments is described in which the blockage of model trash racks was observed and measured by placing the model racks in a refrigerated flume in which frazil ice was produced. The accumulation pattern of the frazil ice on the trash rack was recorded by overhead and underwater video cameras. The trash rack bar spacing and trash rack bar shape were varied and their influence assessed on the head loss through the rack. The porosity of the accumulated frazil was measured. To observe the crystal structure of the accumulation, thin sections were made of the accumulated ice. Based on these experiments, a quantitative understanding of the frazil ice accumulation on intake trash racks can be developed.

LABORATORY EXPERIMENT

Refrigerated flume facility

The experiments were conducted in CRREL's refrigerated flume facility, consisting of a flume, a sump, a reserve storage sump, three centrifugal pumps, heat transfer equipment, manual and automatic valves and in-line electromagnetic flow meters. The flume is located in a refrigerated room where temperature can be controlled from approximately 16 to –29°C. The flume itself is 36.6 m long, 1.2 m wide and 0.61 m deep, and is constructed of aluminum and glass. It is tiltable, with maximum slopes of approximately +0.01 to –0.005. The flow within the flume can be controlled by upstream and downstream sluice gates, as well as by vertical louver gates at the downstream end. Immediately upstream of the flume headbox is a heat exchanger that discharges directly into it. Additional detail concerning the flume facility is available in other publications (Daly et al. 1985, Daly and Colbeck 1986).

During an experiment, approximately 0.026 m^3/s of water was pumped by a nominal 5-hp (3730-W) pump from the flume sump, through the on-line electromagnetic flow meter, and into the heat exchanger. From there the flow was passed into the headbox of the flume and then along the flume, through the model trash rack near the downstream end. The flow then dropped through a free overfall and back into the sump.

The air temperature in the flume facility was typically between –12 and –17°C. The water was slightly supercooled upon leaving the heat exchanger and entering the headbox, where it was seeded with ice crystals that were produced by spraying fine drops of water into the air. The water drops would quickly freeze and a continual "rain" of ice crystals was produced. Seeding was necessary to generate sufficient frazil for the experiments.

Model trash racks

The overall model trash rack dimensions were fixed by the size of the flume. They were installed vertically and perpendicular to the flow (Fig. 1),

Table 1. Outline of the experiments conducted.

Test number	*Bar shape*	*Bar spacing (mm)*	*Maximum head (mm)*	*Total time (min)*
1.1.1	rectangular	25.4	81.7	47
1.1.2	rectangular	25.4	166.0	56
1.2.1	rectangular	47.6	91.9	62
1.2.2	rectangular	47.6	60.7	50
1.3.1	rectangular	60.3	114.0	137
1.3.2	rectangular	60.3	148.0	72
2.1.1	square	25.4	69.6	72
2.1.2	square	25.4	132.0	89
3.1.1	round	25.4	79.8	85
3.1.2	round	25.4	160.0	51
3.2.1	round	47.6	90.0	75
3.3.1	round	60.3	13.4	123
4.1.1	pointed	25.4	71.0	72
4.2.1	pointed	47.6	114.0	65
4.3.1	pointed	60.3	75.5	127

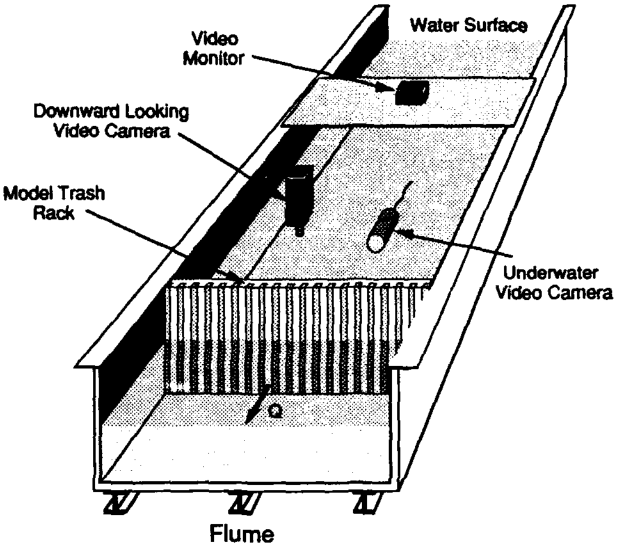


Figure 1. Experimental setup in the refrigerated flume facility.

and were constructed using aluminum bars that were held in place at the top and bottom by horizontal clamps. There were no other horizontal supports for the trash rack bars. The bar spacing was variable and is listed in Table 1. Four different bar shapes—rectangular, square, round and pointed—were used.

Instrumentation

The data collected during the course of an experiment are outlined in Figure 2. The instrumentation that was used to collect this information is discussed in this section.

Water level

Water levels and depths were measured using manual point gauges. These gauges have an accuracy of $\pm^1/_2$ mm.

Temperature

We measured the water temperature and the temperature in the model trash rack bars using individually calibrated thermistors. The thermistors used to measure water temperature were custom mounted in a plastic protector and attached to a Teflon-coated cable, while those used to measure the trash rack bar temperatures were mounted

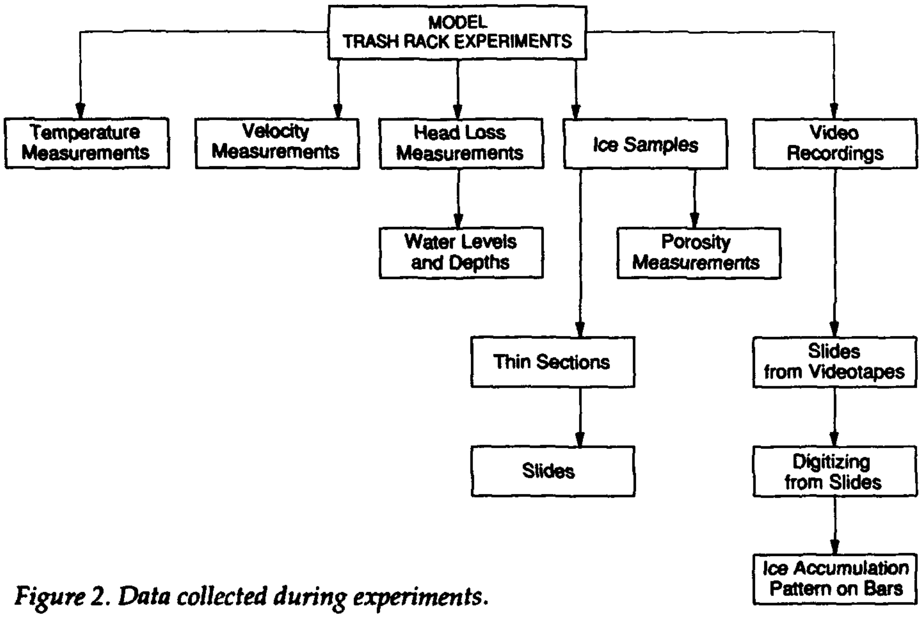


Figure 2. Data collected during experiments.

directly in small holes drilled into the bars, where thermal contact between the thermistors and the bars was assured by use of heat transfer paste. The temperature of all thermistors was found using the CRREL 10-channel digital thermometer (Trachier and Morse 1988). The digital thermometer automatically calculates the thermistor temperature from the thermistor resistance using both the Steinhart–Hart equation with three terms and the calibration constants for each individual thermistor. The temperature data were stored by the digital thermometer and subsequently transferred to the Shared Resource Management system (SRM), a computer network that gave us further analysis and plotting capability on a range of computers. The accuracy of the temperature data is estimated to be ±0.02°C.

Velocity

The water velocity was measured using a Marsh-McBirney Model 511 electromagnetic flow meter. This flow meter consists of a 0.6-cm transducer probe with cable and a signal processor housed in a portable case. The probe measures the flow velocity in two perpendicular directions. The signal processor provides an analog voltage signal that is linearly proportional to the flow velocity. This signal was sampled by an HP3421 analog-to-digital convertor, controlled by an HP71B handheld calculator. The data were recorded by an HP9144A disk drive, and were subsequently transferred to the SRM for analysis and plotting.

The water velocity measurements were made using the following procedure. The probe was positioned and oriented so as to make the flow velocity zero in one of the two directions. We manually entered the x and y location of the probe into the HP71B; the reading was then taken of the flow velocity. Each reading was the average of 10 samples of the flow velocity, taken over a period of approximately 7.5 seconds. The time, location and reading of the flow velocity in each direction were then stored on a magnetic disk, and the process repeated. The accuracy of the water velocity measurements is estimated to be ±2 cm/s.

Porosity

The porosity of the frazil ice deposited on the model trash racks was measured using a modified CRREL snow density kit (Ueda et al. 1975). The snow density tubes were driven into the deposited frazil, capped underwater with rubber end caps, and then had rubber bands applied to hold the end caps in place. The end caps were watertight so that no water drained from the tubes. The tubes were then removed from the water, dried quickly with tissue and weighed. This weight was compared to the tare weight of the tubes, end caps and rubber bands. The weights are estimated to be accurate to 2 g.

Accumulated pattern

The frazil ice accumulation pattern was recorded from above using a standard color video camera recording on $^1/_2$-in. (12-mm) VHS videotape. The underwater recordings were made using a black-and-white video camera, which had a fixed focal length and adjustable focus, that was mounted in a waterproof 0.61-m-long, 6.35-cm-diameter tube. For certain tests we also used a color video camera that had an adjustable focal length and was mounted in a similar tube. The color camera was able to zoom in, allowing it to be placed further upstream from the trash rack.

To provide selected scenes from the videotape record for detailed analysis, 35-mm film slides were made of those scenes using a Polaroid Freeze Frame Video Recorder, with playback provided by a Panasonic 6300 video tape deck. The 35-mm slides were projected on a Talos digitizing tablet, custom mounted in the vertical direction. Dimensions were then taken using the digitizing tablet, which was interfaced with an HP45C computer. The data were transferred to the SRM for further analysis, and long-term storage.

Procedure

Each test was conducted in the following manner. The flume slope and discharge were set. The room temperature was set at approximately –15°C. We found that the room temperature varied throughout the course of a test as much as 2 °C, probably because of normal variations in the refrigeration operations, although ice accumulation on the air handling units and other factors could also be an influence. The water temperature was closely monitored. Generally, immediately before a test, the water temperature would steadily decline. When the water temperature was below 1°C at the location in the flume where the model trash rack was to be installed, the rack was brought into the coldroom and placed in the flume. The downward-looking and underwater video cameras were aligned and started, and the date and time and other relevant information were recorded. When we saw that the water temperature was low enough—supercooled—the seeder was turned on. If ice had collected on the model trash rack before the seeder was started, we removed this ice with warm water, applied by a hose. The test was then begun.

We periodically measured the water levels upstream and downstream of the model rack throughout the test. The downstream water velocities were also measured periodically, either horizontally across the flume at a fixed elevation or vertically at the flume centerline. The test was ended when the upstream water level had doubled or 2 hours had elapsed from the beginning of test. At the end of each test, the seeder was shut off, and warm glycol was circulated through the bottom of the flume. This warming released ice that had accumulated along the length of the flume, and slightly warmed the water so that frazil was no longer produced. The video recordings were stopped, and the tapes labeled. The model trash racks were then removed from the flume and brought into a heated area where the accumulated ice could be easily removed.

An outline of the experiments conducted is shown in Table 1; 15 separate tests were conducted. The tests can be divided into four groups based on the shape of the bars used in the model trash rack—rectangular, square, round and pointed. We used three different spacings between the bars (25.4, 47.6 and 60.3 mm). The length of time that each experiment was conducted varied, depending largely on the rate of head loss at the model racks. Also, during the course of an experiment, anchor ice would accumulate at the bottom and on the walls of the flume. The latent heat released by this ice would cause the water temperature to rise. Eventually, the water temperature at the model trash rack would reach 0°C, and at this point a test would be concluded.

EXPERIMENTAL RESULTS

Head loss

Figure 3 displays the head losses as a function of time through the model trash rack constructed of rectangular bars, with different spacings between the bars. During these tests the discharge through the model trash racks remained constant. In general, increasing the spacing between the trash rack bars increases the time required to reach a specific head loss. Figure 4 shows the measured head loss versus time through the model trash rack constructed of different shaped bars with the same spacing—25.4 mm. It is difficult to draw any specific conclusions regarding the influence of the bar shape on the head loss. Certainly, there does not

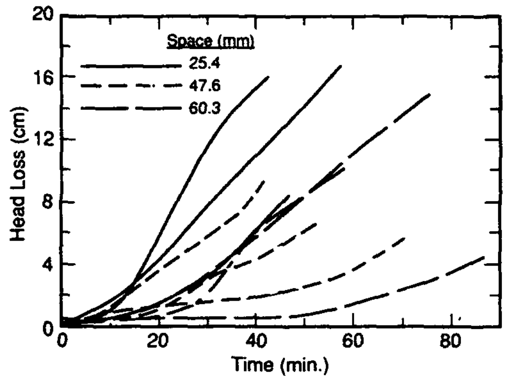


Figure 3. Head loss for rectangular bars vs time, with various spacings between the bars.

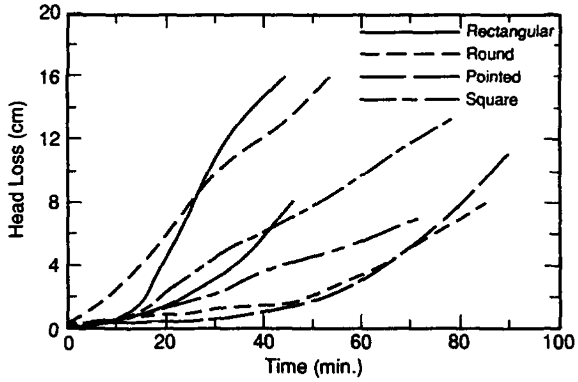


Figure 4. Head loss for different shapes vs time at 25.4-mm spacing.

seem to be a clear advantage of one shape over another. Figures 3 and 4 show that there was considerable variation in the head loss with time for identical trash rack configurations. Possible reasons for this are variations in the frazil concentrations and supercooling levels. It is likely that for trash racks with the same bar spacing, the time to reach a certain head loss decreases with increasing frazil concentration.

Temperature measurements

Examples of the temperature measurements made during the course of an experiment are shown in Figures 5 and 6. The water temperatures upstream and downstream of the model rack are shown in Figure 5. A near constant level of supercooling was maintained during a test, although it was reduced near the end. This probably reflects the latent heat released by growing anchor ice that had collected in the flume upstream of the model trash rack over the course of the test.

Temperatures measured in the trash rack bars are shown in Figure 6. At the start of each test,

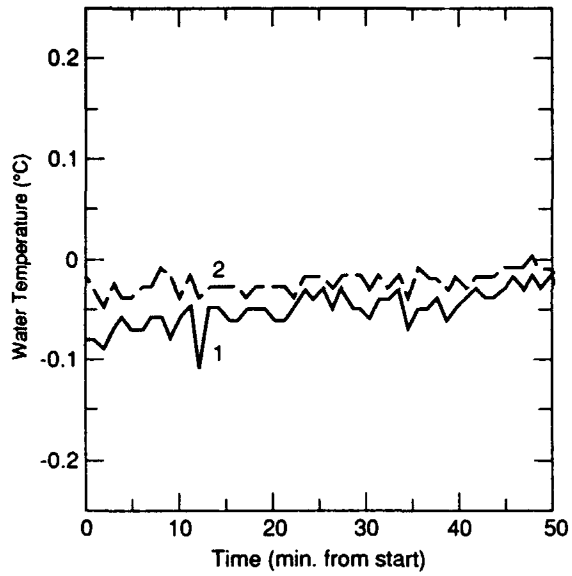


Figure 5. Water temperature measurements during test 1.2.2. Curves 1 and 2 show the temperature upstream and downstream the trash rack respectively.

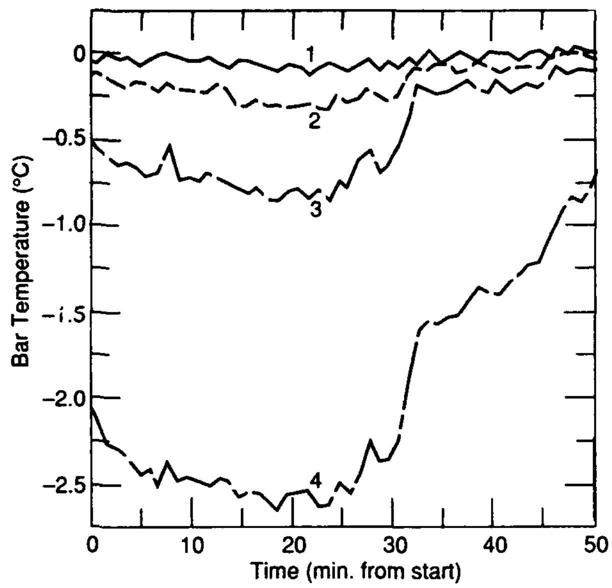


Figure 6. Bar temperature measurements during test 1.2.2. Curves 1 and 2 show the submerged thermistors; curves 3 and 4 are for the thermistors below and above the initial water level respectively.

thermistors 1 and 2 were submerged, thermistor 3 was slightly below the starting water level and thermistor 4 was just above the starting water level. The temperatures of the bars were all above 0°C prior to the start of a test, reflecting that the model trash rack had been brought into the coldroom from a warm preparation area immediately before the start of a test. During the course of a test, as ice collected on the trash rack bars, the upstream water level would rise and downstream water level would tend to drop. The temperatures of the thermistors located higher on the bar would initially decline, reflecting heat conduction through the trash rack bar, and the exposure of the back side of the bars owing to the drop in the downstream water level. This can be seen in the decrease in temperature that occurred at each thermistor. The extent of the decreases is proportional to the elevation of the thermistor: the higher on the bar that the thermistor was located, the greater its exposure to the cold air.

Velocity profiles

Velocity profiles were measured downstream of the model trash rack with the Marsh-McBirney electromagnetic flow meter. Profiles were taken across the flume at a depth equal to one-half of the initial downstream flow depth. Typical results are shown in Figure 7. The velocity profiles are initially quite uniform across the width of the flume, indicative of the uniformity of the flow through the model trash rack. A higher velocity through bar spaces 20, 22 and 24 can be seen in the second profile, which was recorded 15 minutes after the first. These higher velocity regions indicate the start of the formation of jets through the trash rack, as frazil ice begins to accumulate on the rack, and the head losses across the rack increase. The third profile, taken 15 minutes later, shows the continued development of the jets. The fourth profile, taken 30 minutes after the third, shows the extreme variation possible after extensive frazil ice accumulation has built up on the trash rack.

Figure 8 gives the development of a vertical velocity profile taken in the centerline of the flume, immediately downstream of the trash rack. The vertical profiles can be roughly divided into three groups. The first group represents the time when there was no or minimal ice accumulation on the trash rack. The maximum velocity occurs near the midpoint of the depth. The influence of the bottom horizontal support of the model trash rack can be seen in the very low velocities near the bottom of the profiles. As the trash rack ice accumulates, the maximum velocity increases, the maximum is closer to the flume bottom, and the velocities near the top decrease and begin to go negative, representing flow in the upstream direction. This second phase takes place because of the accumulation of ice on the top of the rack. Jets begin to form, and

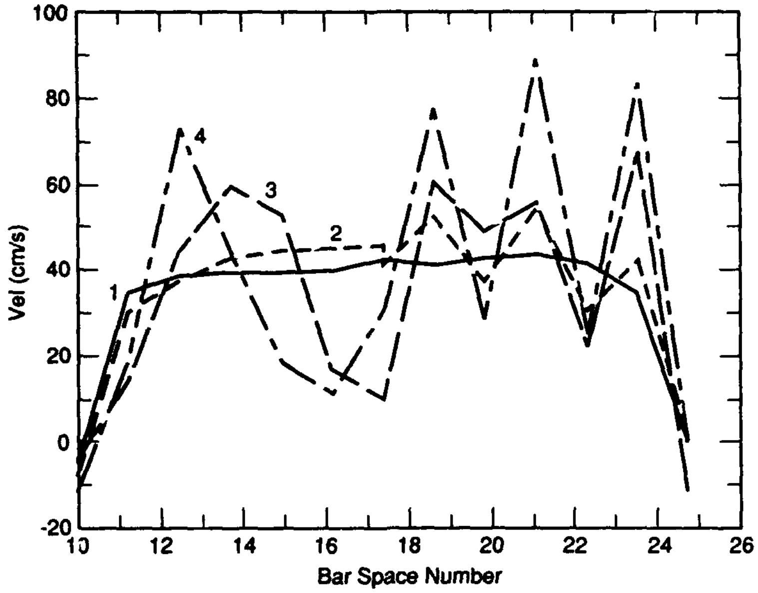


Figure 7. Velocity measurements across the trash rack during test 3.1.1. Numbers refer to order in which profiles were taken.

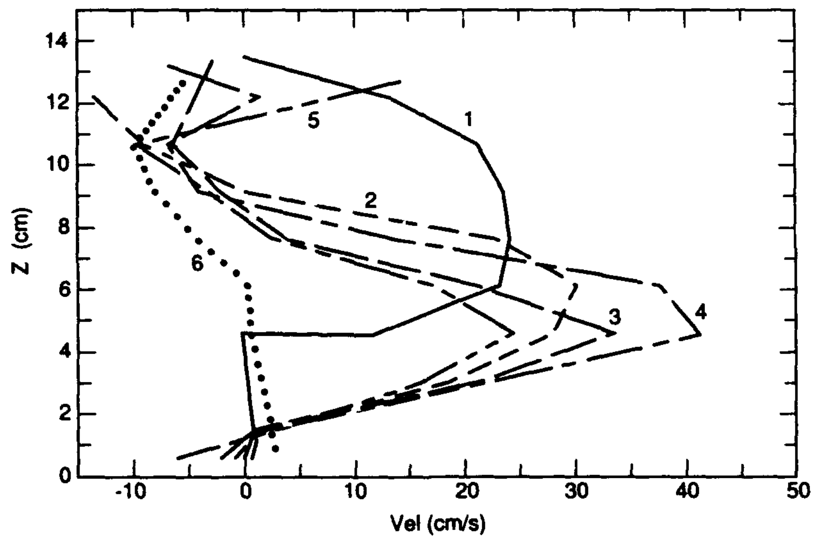


Figure 8. Vertical velocity measurements downstream of the centerline of the trash rack during test 1.1.2. Numbers refer to order in which profiles were taken.

a large, horizontal "roller" type of current can be seen. The formation of these jets has been noted in the field, where they have been quite erosive. The third phase results when the trash rack is nearly plugged in the vicinity of its centerline. Little flow is passing through the rack, and the velocity is quite low throughout the depth.

Porosity of the deposited frazil

We found the porosity of the deposited frazil by weighing 3 cm^3 of the accumulated mass of the frazil taken from the trash rack. The porosity e is then calculated as

$$e = \frac{\frac{m_s}{V_m} - \rho_i}{\rho_w - \rho_i}$$

where m_s = mass of sampled frazil
V_m = volume of the cylinder
ρ_i = density of ice (916 kg/m^3)
ρ_w = density of water (1000 kg/m^3).

A total of 20 samples was measured. The mean porosity of the samples was 0.67, with a standard deviation of 0.13 (Fig. 9).

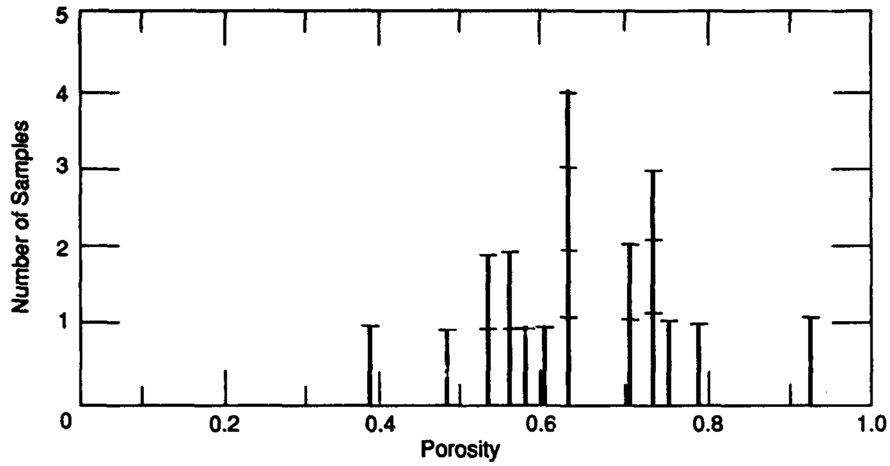


Figure 9. Porosity measurements of deposited frazil ice at the front of the trash rack.

Accumulation pattern

The accumulation patterns of the frazil ice on the trash rack bars are shown in Figures 10 and 11. Figure 10 gives views of the ice accumulation at the water line of the bars as seen by the video camera above the water. There is a basic pattern of accumulation. The initial ice accumulates on the upstream side of the bars. The ice then extends upstream into the flow and increases in width. At a certain point, the accumulated ice bridges across two successive bars. While not visible in the figures, we identified two types of bridging across the bars by closely inspecting the videotapes. The first type is the joining together of the frazil that accumulates on the upstream face of each bar. The second is when the accumulation on a bar is pushed to one side by the flow. The bridging then happens very rapidly, leaving a gap on the opposite side of the bar. This gap may remain open or be bridged by a process of the first type. Another feature that we noted by inspecting the videotapes is that a large portion of the initial accumulation on the bars may be removed several times in quick succession by the flow. However, eventually the accumulation remains and extends upstream.

Figure 11 gives views of the trash rack that can be seen by the underwater video, and is representative of all the tests. The frazil ice accumulation progresses downward on the trash rack, although the time for the ice to progress downward was much longer than the time for the initial bridging at the water's surface. In general, the bridging at the water surface occurred first, and then the downward progression began.

Thin sections

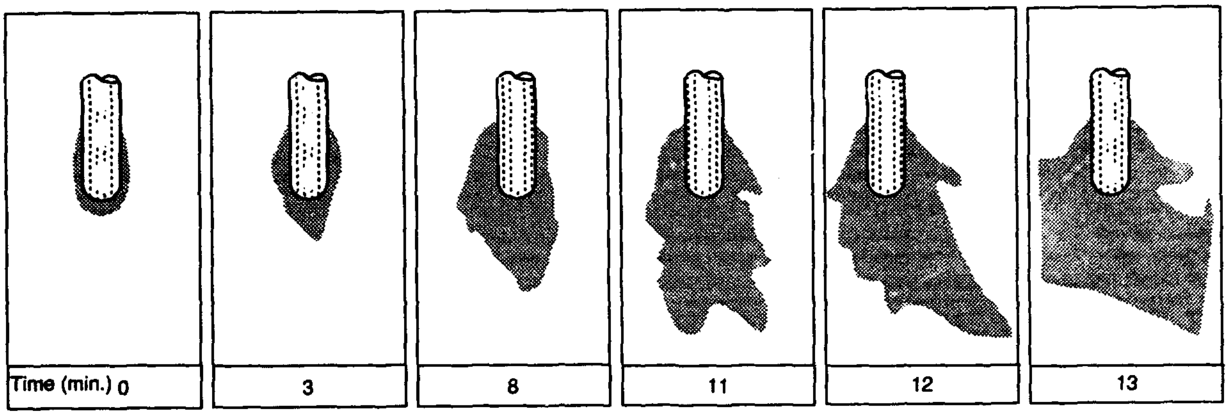
Thin sections are often used to study the crystal structure of ice. There are no previous reports in the literature of thin sections being taken of frazil ice accumulated on trash rack bars. In this work horizontal thin sections at different elevations were taken and photographed through cross polarized glass.

The thin sections were made in the following manner. At the end of a test, the water level in the flume was slowly lowered to allow the frazil ice that had accumulated on the rack to freeze and gain strength. If this was not done, the ice would fall apart, owing to its low cohesion, high porosity and relative heaviness. When the water had been drained from the flume, the trash rack bars were removed with the samples of ice intact. The trash rack bars were then heated slightly and removed from the sample, after which thin sections were cut. The thin sections had to be very thin (average thickness of 1.2 mm) because of the small size of the frazil crystals.

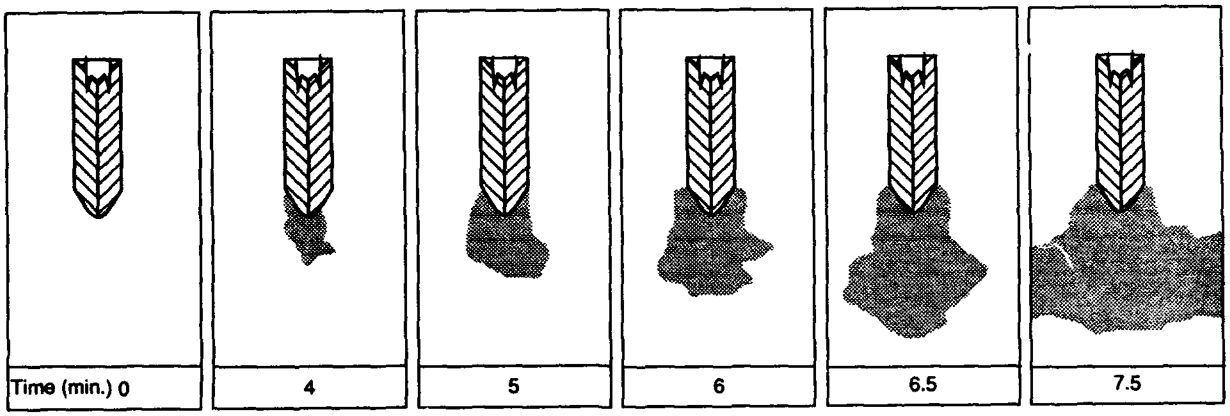
Horizontal thin sections were taken at various levels throughout the sample and are shown in Figure 12. Thin sections of ice accumulation at the initial water level for different shapes are shown in Figure 13. Generally, the ice in the thin sections is very fine grained, except immediately next to the trash rack bars. Here, the ice crystals are much larger and may reflect the influence of thermal growth attributable to heat transfer from the bars. It is not clear if these crystals grew before or after the frazil crystals had accumulated on the bars.

DISCUSSION

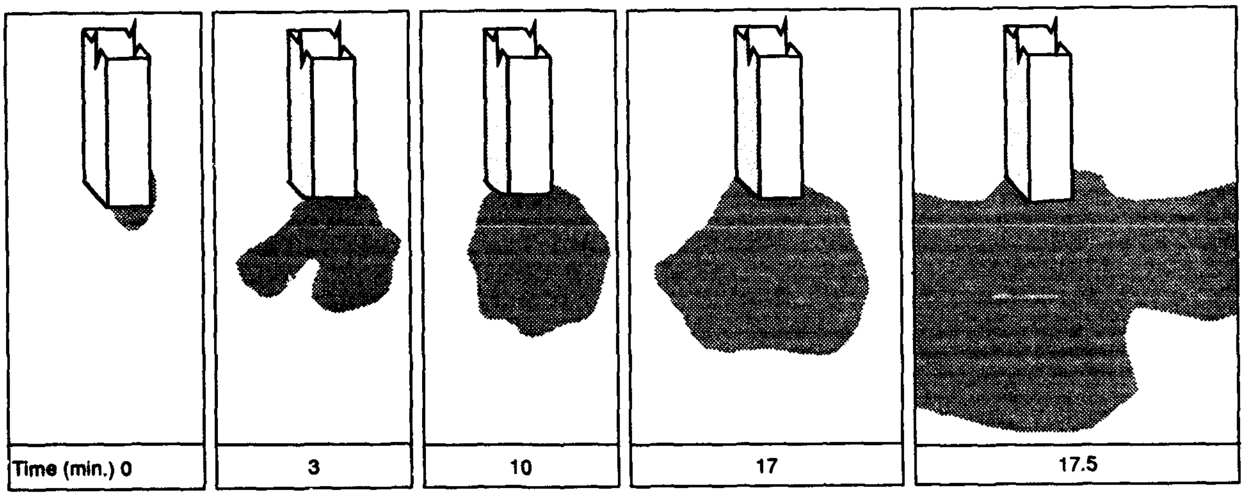
A major goal of these tests was to investigate the ice accumulation patterns on intake trash racks. The accumulation pattern was consistent, regard-



a. Round bar, test 3.1.1.

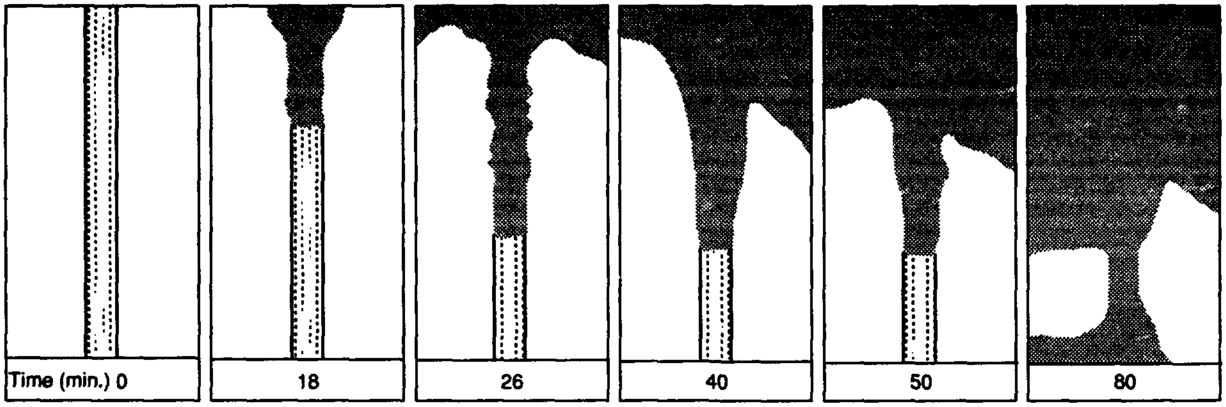


b. Pointed bar, test 4.1.1.

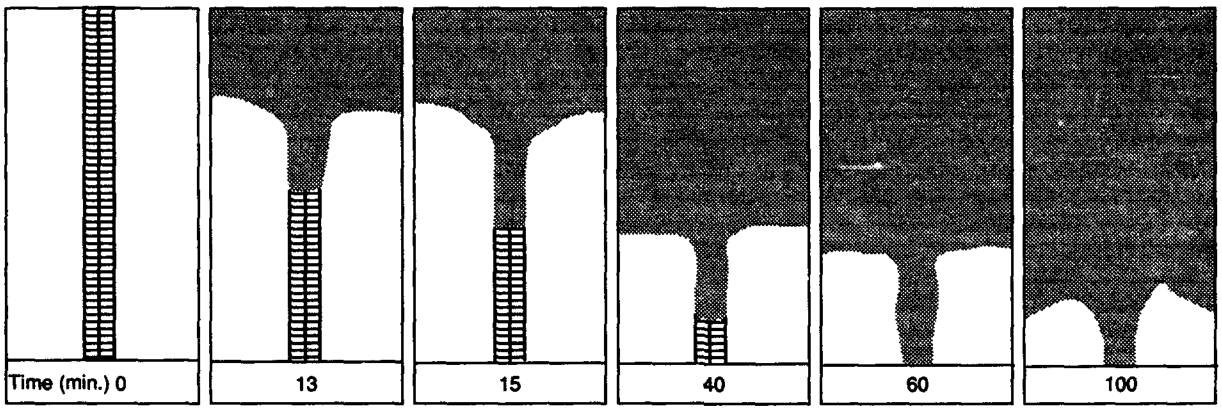


c. Rectangular bar, test 1.2.2.

Figure 10. Ice accumulation patterns at the water surface (flow is from the bottom of the figures to the top).



a. Round bar, test 3.1.1.



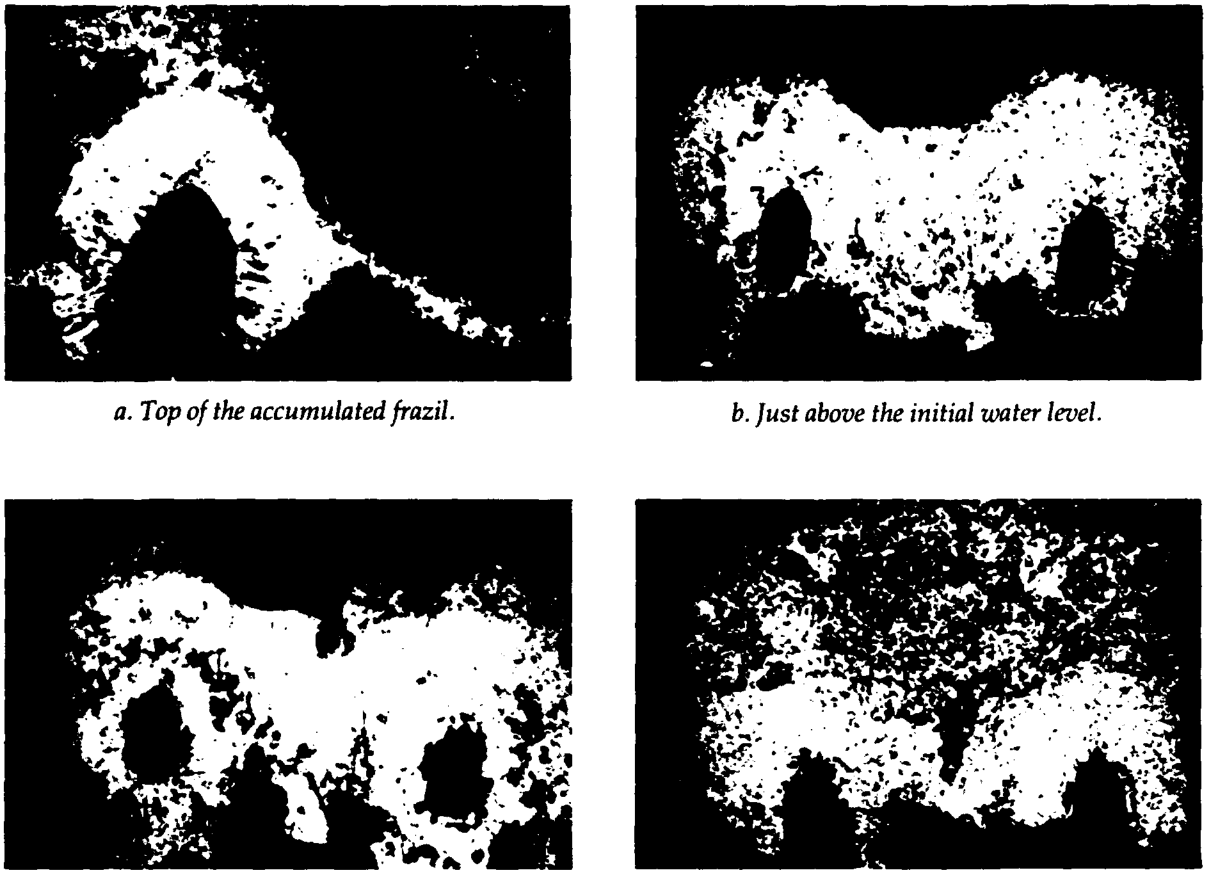
b. Pointed bar, test 4.1.1.

Figure 11. Vertical ice accumulation patterns (flow is directly into the figures).

less of the bar shape or spacing of the bars. The frazil ice would start to accumulate first at the water surface, and would then extend upstream into the flow. The accumulation would bridge between the bars, first at the water surface, and then it would progress downward. This downward progress of ice accumulation on intake trash racks has also been observed and documented by the first author at a field site. Ice may accumulate first at the water surface for three reasons. First, this is the location where the trash rack bar, in contact with the water, is the coldest, and the low temperatures may increase the adhesion strength between the frazil crystals and the bars. Second, the frazil concentration may be highest at the surface. While there are no quantitative measurements to show if this is true or not, the buoyancy of the larger crystals, and of the flocs of crystals, could easily increase the concentration of crystals at the surface. The video observations above and below the water cannot really decide this. The last reason is suggested by the thin sections, which show relatively large congelation crystals extending from the trash rack bars at the original water line. Before there is any accumulation on the trash rack bars, minute variations in the water surface at the bars could coat them with a thin glaze of thermally grown ice immediately at the water line. This glaze would then promote the additional accumulation of deposited frazil ice.

Just as the accumulation pattern is independent of the bar shape, so is the measured head loss through the rack. The head loss is definitely influenced by the spacing of the trash rack bars, however. In general, the larger the spacing between trash rack bars, the longer the time until a specific head loss was reached. This suggests that trash racks should be designed with the maximum space possible between the bars, given the practical realities of trash rack strength and the size of objects that can be accepted downstream.

The thin sections show that, except for a very small region immediately next to the trash rack bars, almost all of the frazil ice accumulated on the



a. Top of the accumulated frazil.

b. Just above the initial water level.

c. At the initial water level.

d. Close to the bottom.

Figure 12. Thin sections taken at various levels in test 4.2.1.

trash rack bars is deposited from the flow. Very little is grown thermally, either by heat conduction through the bars or by the transfer of latent heat to the flowing supercooled water. This supports earlier calculations (Daly 1987) that indicated that the mass of deposited ice would dominate over that grown through heat transfer on trash racks.

SUMMARY

A number of tests were conducted in a refrigerated flume facility in which we watched as model trash racks accumulated ice and became blocked. The accumulation pattern of the frazil ice on the racks was recorded, and measurements of the flow velocity and water temperature were made throughout the tests. In addition, the porosity of accumulated frazil ice was measured and thin section were taken of the accumulated ice. From these measurements and observations the following general statements can be made.

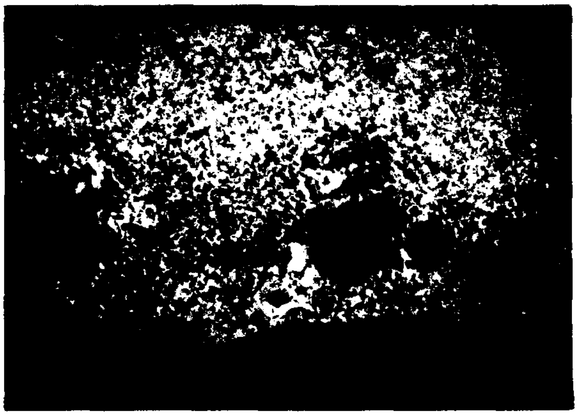
1. The frazil ice accumulates first on the upstream side of the trash rack bars. The accumulation pattern is similar for different bar shapes, suggesting that the accumulation of ice on intake trash racks is insensitive to the shapes of the bars.

2. The frazil ice accumulation bridges between individual bars first near the water surface. The bridging then proceeds downward until the entire trash rack is blocked.

3. The flow through the rack, while at first fairly uniform, can become highly nonuniform as the frazil ice accumulates and bridges across various bars. High velocity flow regions are formed in areas where the bridging occurs late, and they persistently remain. The locations and number of these high velocity flow regions appear to be randomly distributed.

4. The accumulated frazil was fairly porous, with a mean porosity of 0.67.

Further work remains to be done to measure the actual frazil concentration approaching the rack,



a. Round bar, test 1.3.2.

b. Square bar, test 2.1.2.

c. Rectangular bar, test 3.1.2.

Figure 13. Thin sections for different shapes taken at the initial water level.

the collision efficiency of the frazil particles with the trash rack bars and the adhesion characteristics of the frazil ice with the trash rack bar material. Unfortunately, this work must wait until the development of new instrumentation and accepted techniques.

Observation of trash rack freezeup in the field at operating water intakes would also be beneficial. Comparing ice accumulation patterns in the field with those in the laboratory would allow greater confidence to be placed in the laboratory results. Numerical modeling of trash rack blockage would also be beneficial.

LITERATURE CITED

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1992	

4. TITLE AND SUBTITLE
Laboratory Investigation of Trash Rack Freezeup by Frazil Ice

5. FUNDING NUMBERS
Ice Engineering Program
WU: 32397

6. AUTHORS
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72 Lyme Road
Hanover, New Hampshire 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER
CRREL Report 92-16

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Chief of Engineers
Washington, D.C. 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

Available from NTIS, Springfield, Virginia 22161.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

A series of tests was conducted in a refrigerated flume facility to determine the ice accumulation pattern on models of water intake trash racks. Data gathered included the flow velocity, the water temperature and the porosity of the accumulated frazil ice (mean porosity is 0.67). Frazil accumulates first on the upstream face of the trash rack bars (being insensitive to bar shape), and then bridges between individual bars near the water surface, proceeding downward until the entire trash rack is blocked. Flow through the rack became highly nonuniform during the accumulation process.

14. SUBJECT TERMS
Frazil ice — Laboratory tests
Freezeup — Trash racks

15. NUMBER OF PAGES 16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

☆U.S. GOVERNMENT PRINTING OFFICE: 1992-600-063/60023

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102